Neutrino Scattering Experiments: What do oscillation expermients need?

Proton Driver Physics Study Workshop
Joint WG1 WG2 session

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October 7, 2004

Acknowledgements & References

- Information taken from:
  - T2K, T.Nakaya, NuINT04 Talk
  - MINOS, N.Tagg, NO-VE, 2003
  - Off-Axis-NOTE-SIM-24, P. Litchfield et al
  - NOνA proposal
  - H. Gallagher, S. Boyd, D. Casper, MINERνA MC authors
- Much of this can be found on this topic at: hep-ex/0410005 hot off the press!

Outline

- Introduction
  - How to measure probabilities with neutrinos
- ν_e appearance
  - NOνA
- ν_μ disappearance
  - MINOS
  - T2K

$$P(\nu_\mu \to \nu_e) \approx \frac{1}{2}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2 L}{4E}\right) + \ldots$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

These are mostly case studies…

Probabilities

$$N_{far} = \phi_{\nu_\mu} \sigma_{\nu_x} P(\nu_\mu \to \nu_x) \varepsilon_x M_{far} + B_{far}$$

ϕ=flux, σ= cross section ε=efficiency M=mass

$$P(\nu_\mu \to \nu_x) = \frac{N_{far} - B_{far}}{\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far}}$$

B_{far}= Backgrounds at far detector, from any flux

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i} (P) \sigma_{\nu_i} \varepsilon_{ix} M_{far}$$

NuINT matters for Signal and Background Cross sections, and indirectly for efficiencies!

Probabilities, continued

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + \frac{N_{far} - B_{far}}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)^2}[\delta(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)]^2$$

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + \frac{(N_{far} - B_{far})}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)^2}\left(\left[\frac{\delta\phi_{\nu_\mu}}{\phi_{\nu_\mu}}\right]^2 + \left(\frac{\delta\sigma_{\nu_x}}{\sigma_{\nu_x}}\right)^2 + \left(\frac{\delta\varepsilon_{\nu_x}}{\varepsilon_{\nu_x}}\right)^2\right)$$

2 Regimes:

$$N_{far} >> B_{far}$$

$$N_{far} \approx B_{far}$$

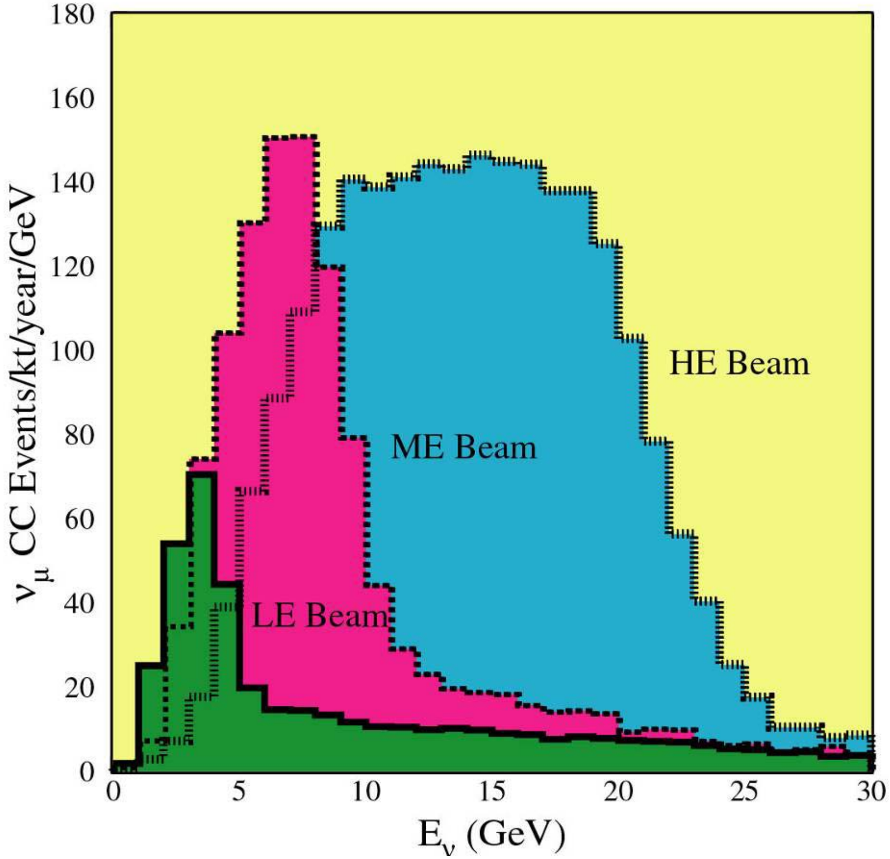
Problem:

Don't always know *a priori* which regime you are in

---depends on Δm^2,

---depends on $\sin^2 2\theta_{13}$

Neutrinos from NuMI



ν_μ CC Events/MINOS/2 year

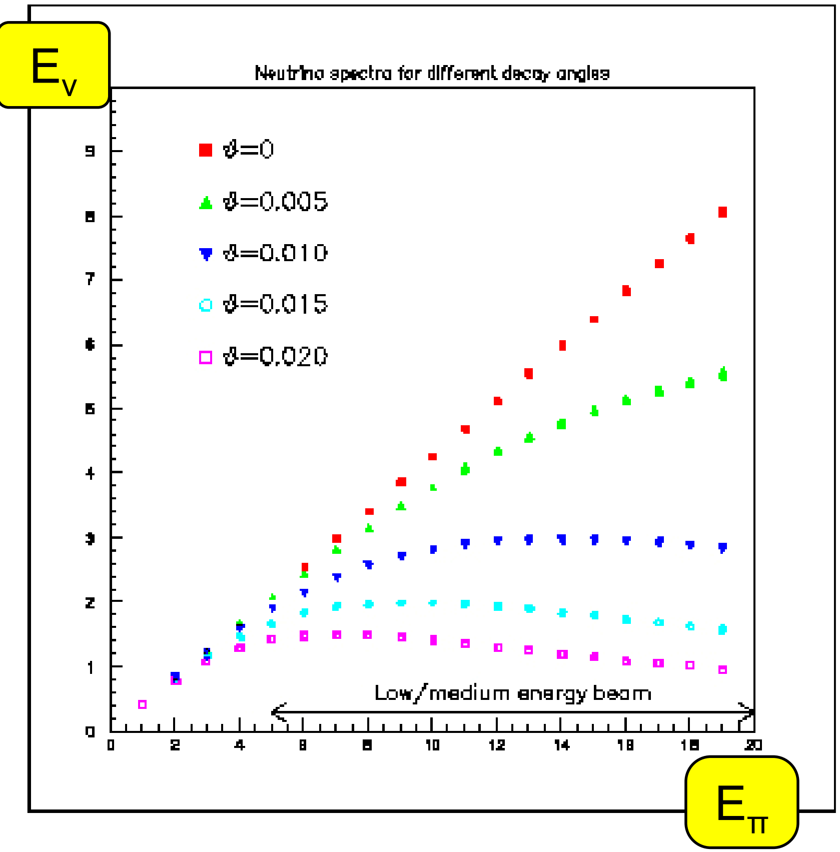
Low	Medium	High
5080	13800	29600

For $4\text{x}10^{20}$ protons on target/year

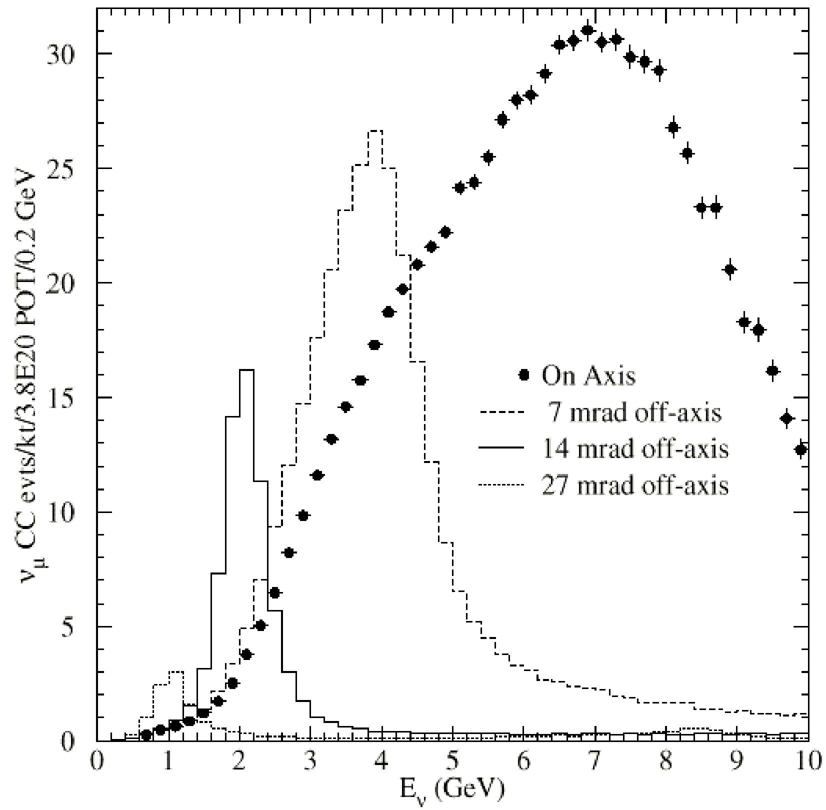
With oscillations about half the ν_μCC events in low energy running will not occur—still in high signal statistics regime!

By moving the horns and target, different energy spectra are available using the NuMI beamline.

NUMI Beams Off-Axis:



NuMI beam can produce 1-3 GeV intense beams with well defined energy in a cone around the nominal beam direction

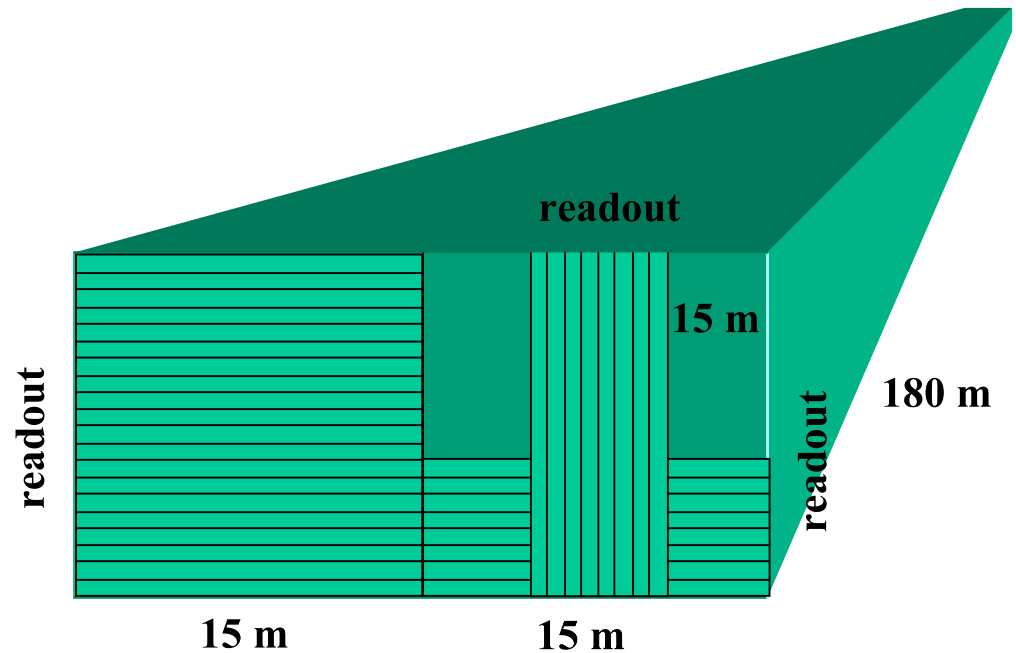


W/o oscillations: 820km, 14mrad: 18.6k ν_μCC, 5.6k NC, 391ν_eCC (50kton detector, 5 years)

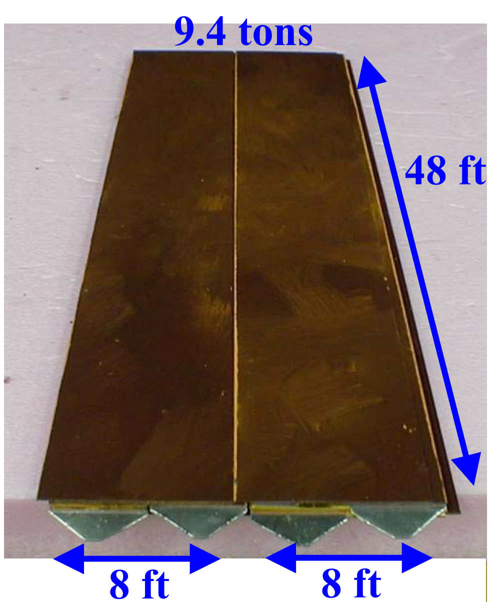
Liquid Scintillator

- Alternating horizontal and vertical scintillator planes
- Passive material: wood Oriented Strand Board (density .6 - .7 g/cm^3)
- Sampling: 1/3 rad. length

Fiducial fraction (1 m cut at all edges) 80%

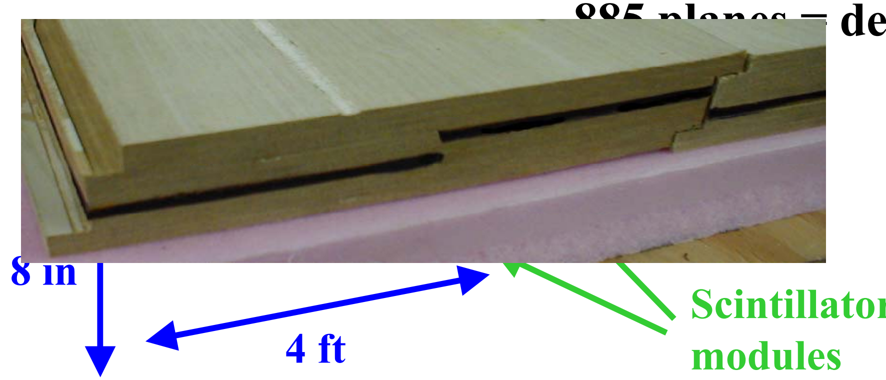


885 planes = detector



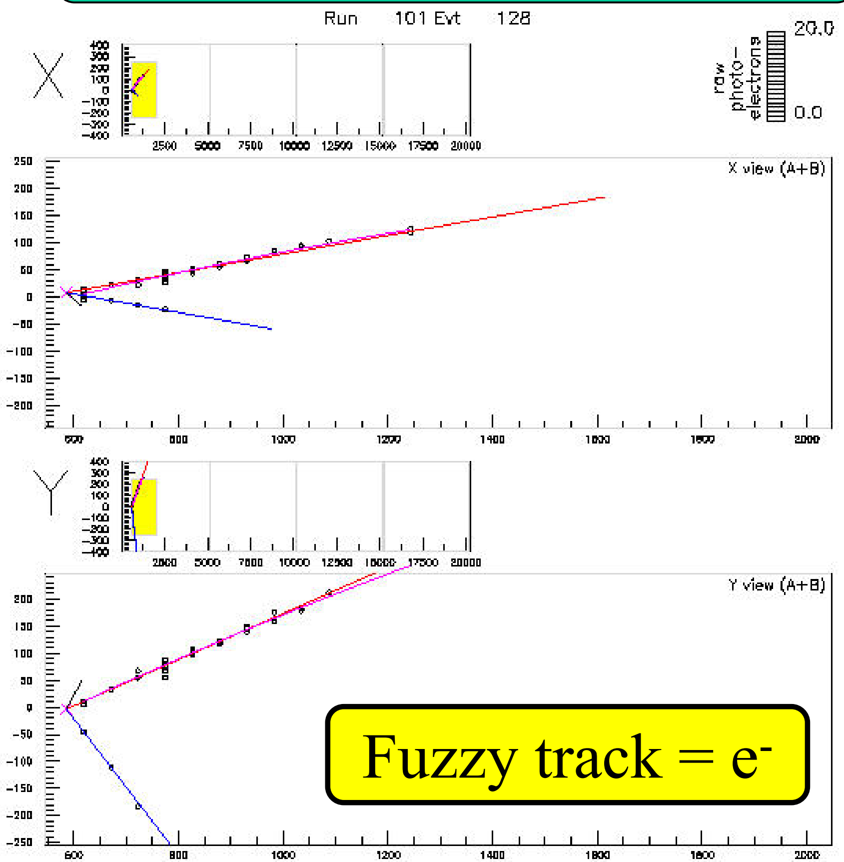
6 = 1 plane

5300 = detector

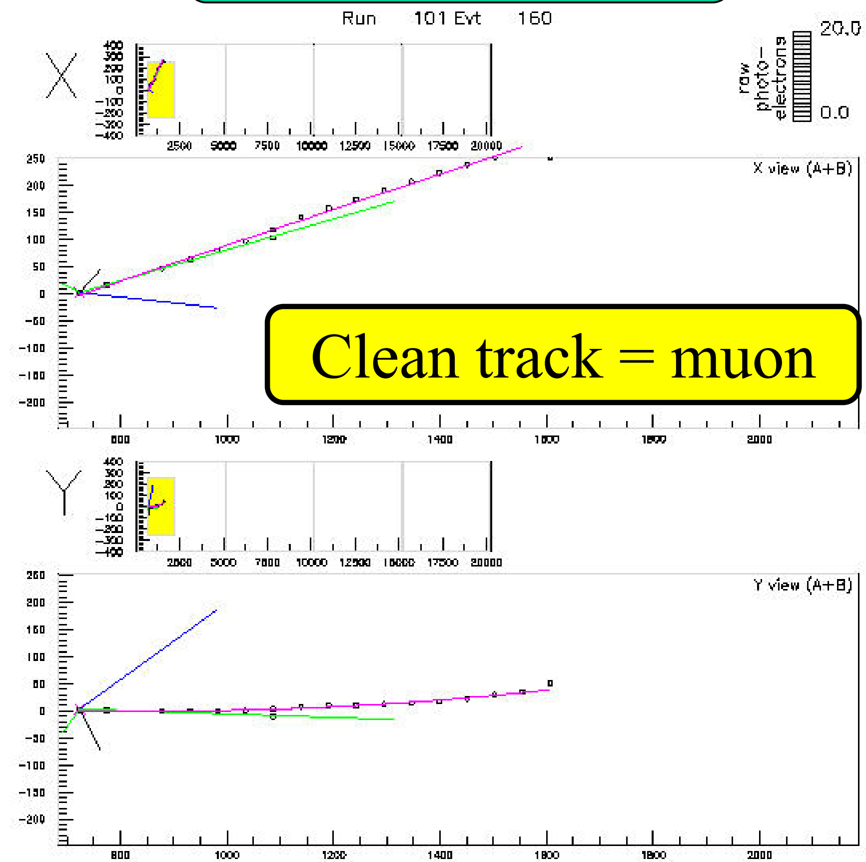


Electron and Muon Tracks

typical signal event

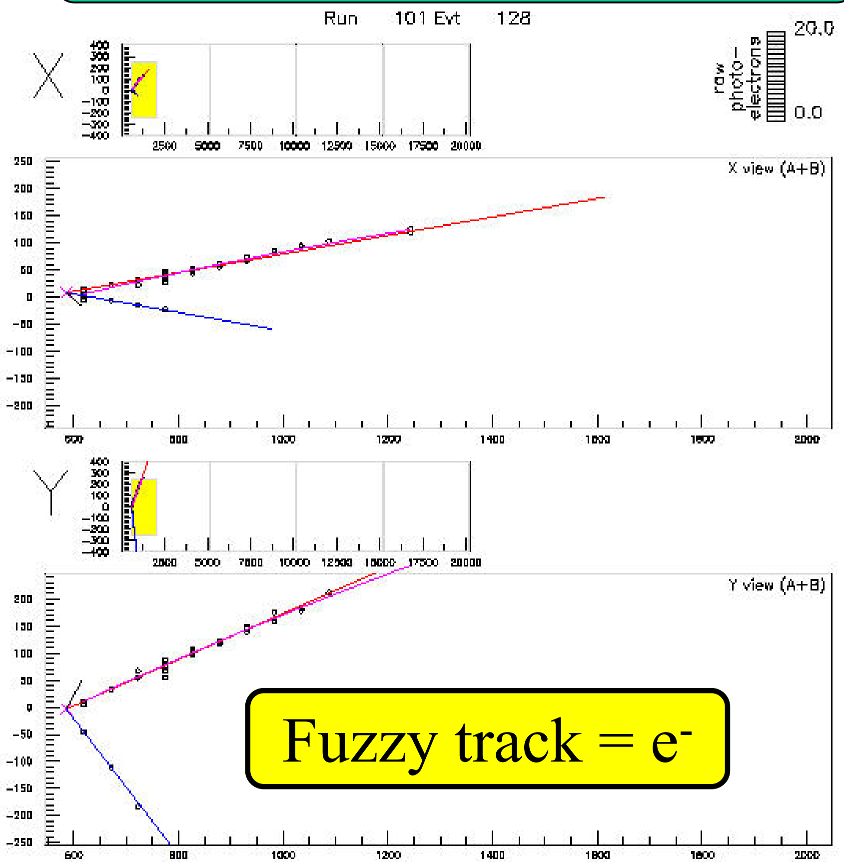


muon QE event

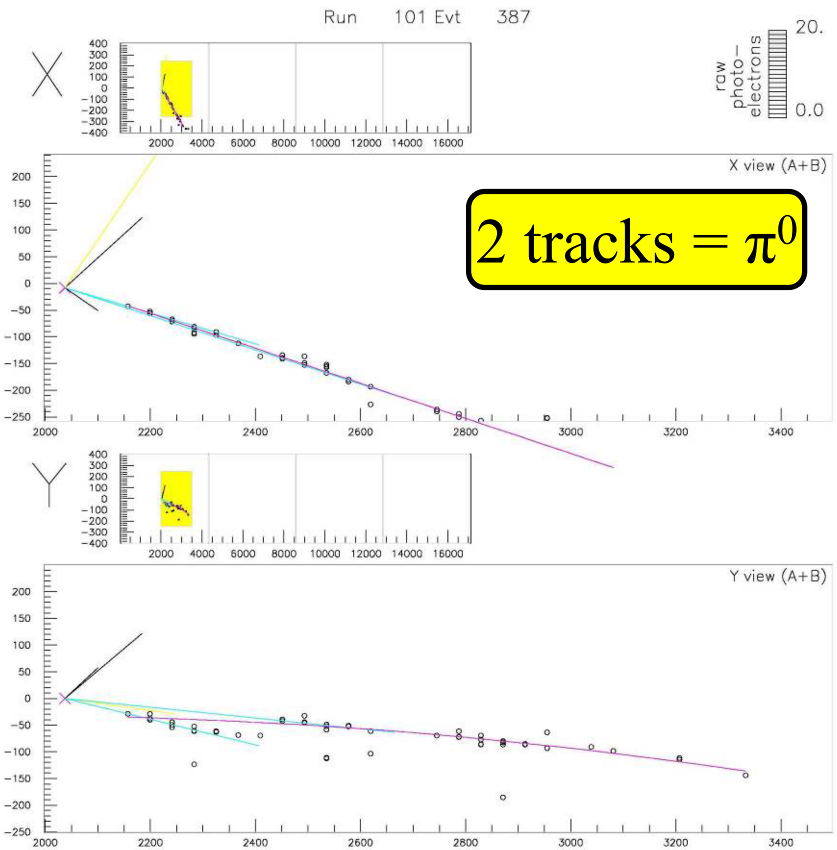


Signal & Background Events

typical signal event



BG event



Near Detector Strategy

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i\,far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}$$

Backgrounds come from several sources

$$N_{near} = \sum_{i=\mu,e} \phi_{\nu_i\,near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}$$

Build near detector with same ε

$$B_{far} = N_{near}\frac{\sum_{i=\mu,e} \phi_{\nu_i\,far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}}{\sum_{i=\mu,e} \phi_{\nu_i\,near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}}$$

Simulations better at predicting ratios absolute levels

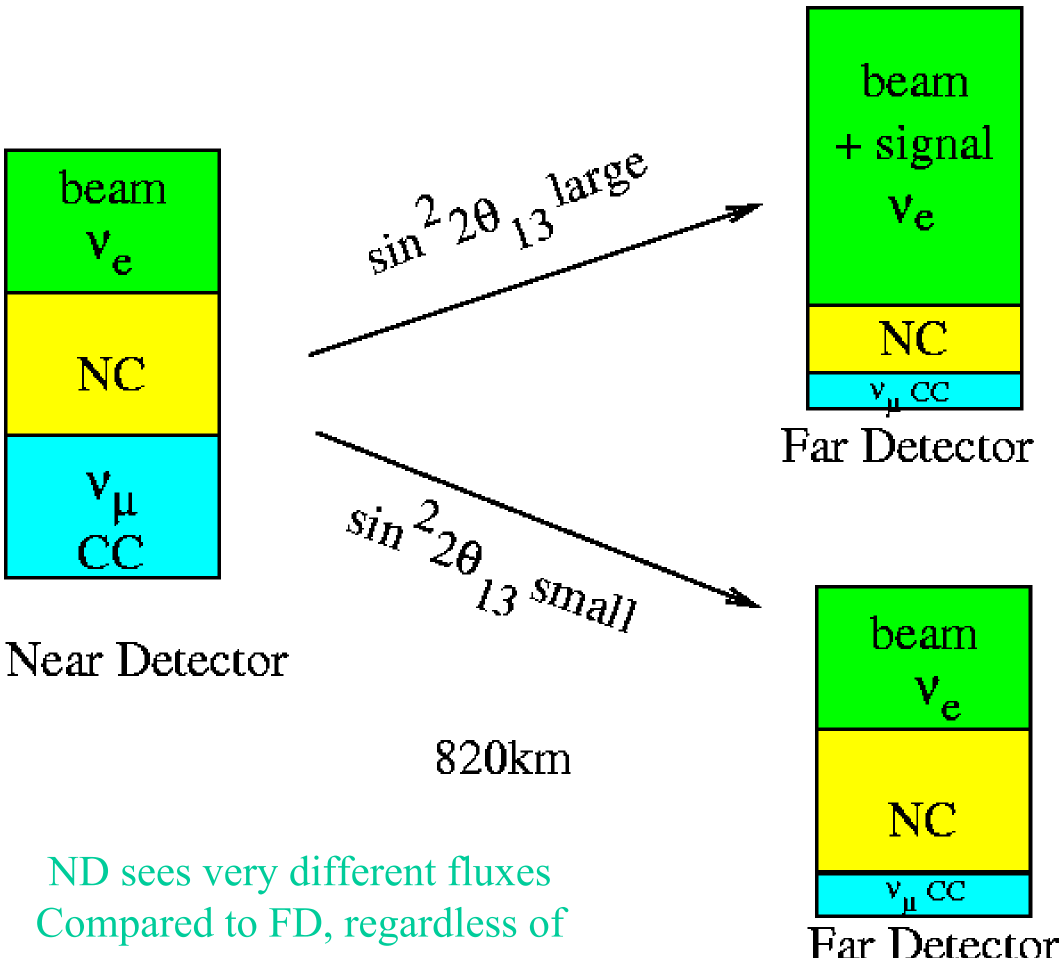
$$B_{far} = \sum_{i=\mu,e} N_{near,i}\frac{\phi_{\nu_i\,far}}{\phi_{\nu_i\,near}}\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}}\frac{\varepsilon_{ix}}{\varepsilon_{ix}}\frac{M_{far}}{M_{near}}$$

Near Detector Strategy (cont'd)

$$B_{far} = \int dE_\nu \sum_{i=\mu,e} N_{near,i}(E_\nu)\left(\frac{\phi_{\nu_i\,far}}{\phi_{\nu_i\,near}}\right)(E_\nu)\left(\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}}\right)(E_\nu)\left(\frac{\varepsilon_{ix}}{\varepsilon_{ix}}\right)(E_\nu)\frac{M_{far}}{M_{near}}$$

- But ratios don't cancel everything
- Underlying problem: fluxes are different
  - Near detector: line source, far detector: point source
  - But even if that is solved, still ν_μCC oscillations
- All of these terms are functions of energy
  - Uncertainties in energy dependence of cross sections translate into far detector uncertainties…

Measuring $\nu_\mu \rightarrow \nu_e$ at NOvA



Assuming 50kton,
5 years at 4×10^{20} POT, $\Delta m^2=2.5\times10^{-3}eV^2$

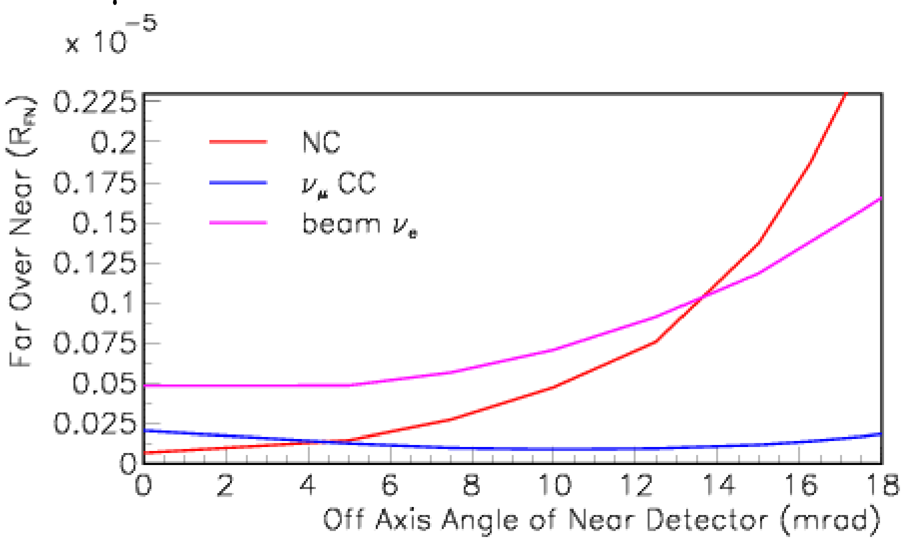
Process	**Events**	QE	RES	COH	DIS
$\delta\sigma/\sigma$		20%	40%	100%	20%
Signal ν_e	**175 At $\sin^2 2\theta_{13}$ =0.1**	55%	35%	n/i	10%
NC	**15.4**	0	50%	20%	30%
ν_μCC	**3.6**	0	65%	n/i	35%
Beam ν_e	**19.1**	50%	40%	n/i	10%

For large $\sin^2 2\theta_{13}$, statistical=8%
For small $\sin^2 2\theta_{13}$, statistical=16%

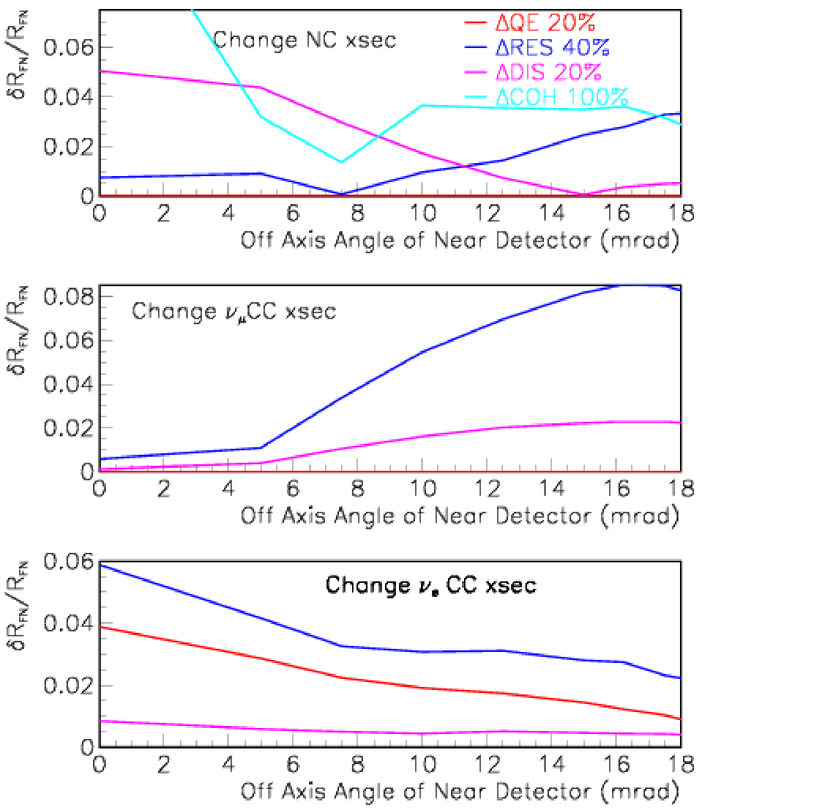
ND sees very different fluxes
Compared to FD, regardless of
Off axis angle of ND!

How well do uncertainties cancel…

- No matter where the ND is, ν_μCC background is very different near to far, because of $\nu_\mu \rightarrow \nu_\tau$ oscillations



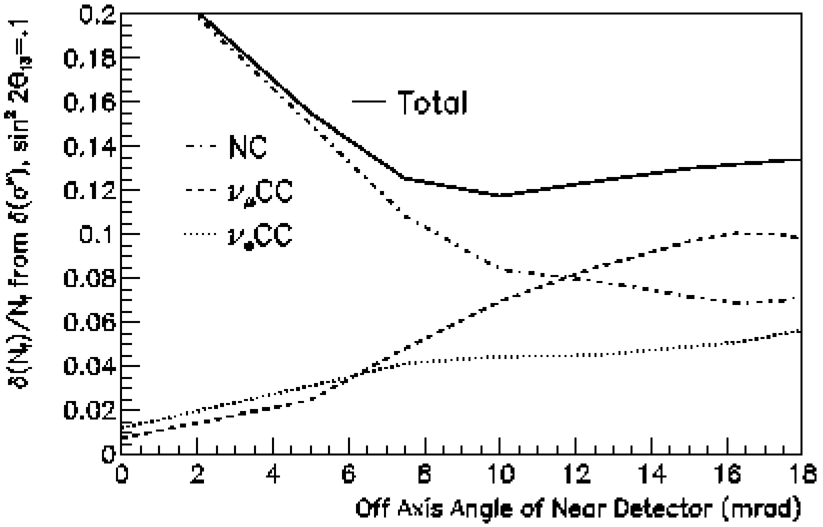
Assume Energy Dependence Perfectly known….vary σ levels



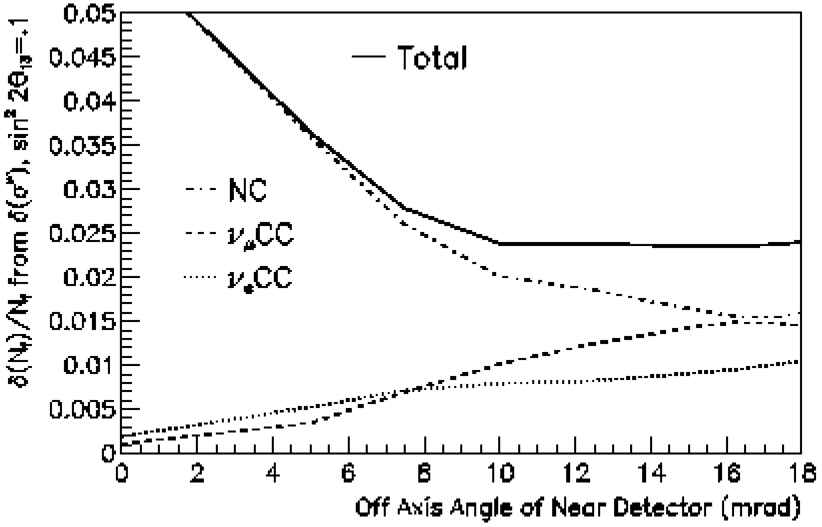
Moral of Story: Need Near Detector AND cross section measurements!

Once a signal is seen at Far Detector…

Current cross section errors



Minerva cross section errors

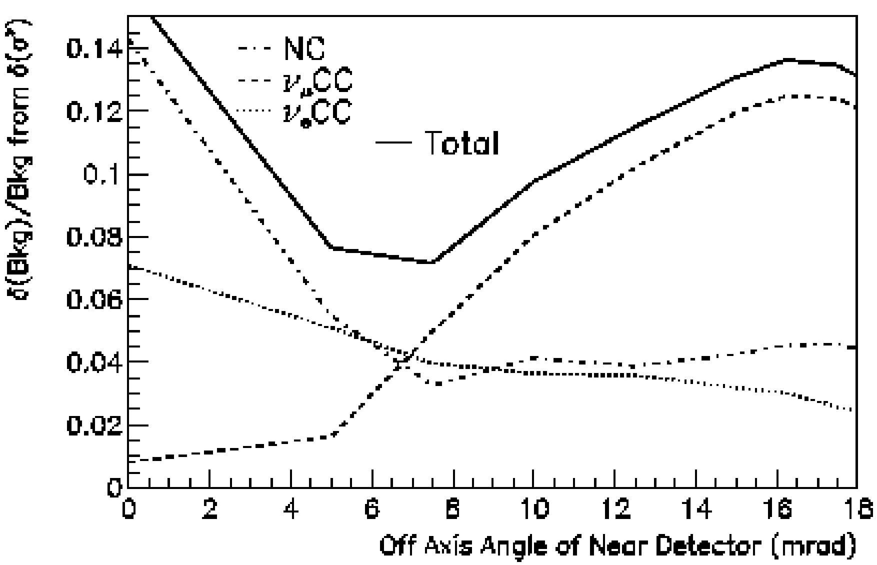


- Recall that statistical error is about 8% here (assuming a "$\sin^2 2\Theta_{13}$" of 0.1!)
- And this is for 0.4MW x 5 years of running

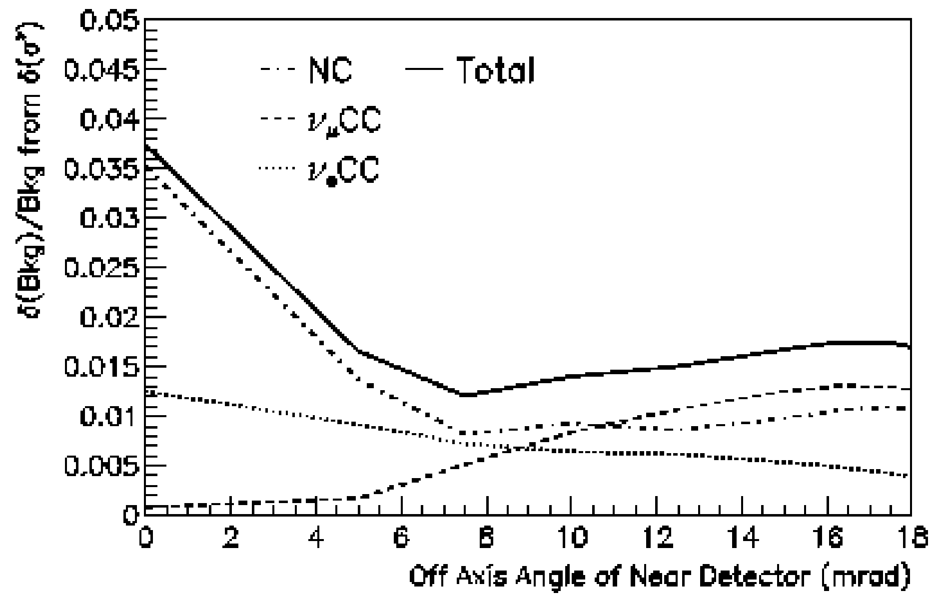
Process	QE	RES	COH	DIS
$\delta\sigma/\sigma$ now	20%	40%	100%	20%
$\delta\sigma/\sigma$ in 2014 (@PD)	5%/na	5%/10%	5%/20%	5%/10%

Background Prediction at Far Detector:

Current cross section errors

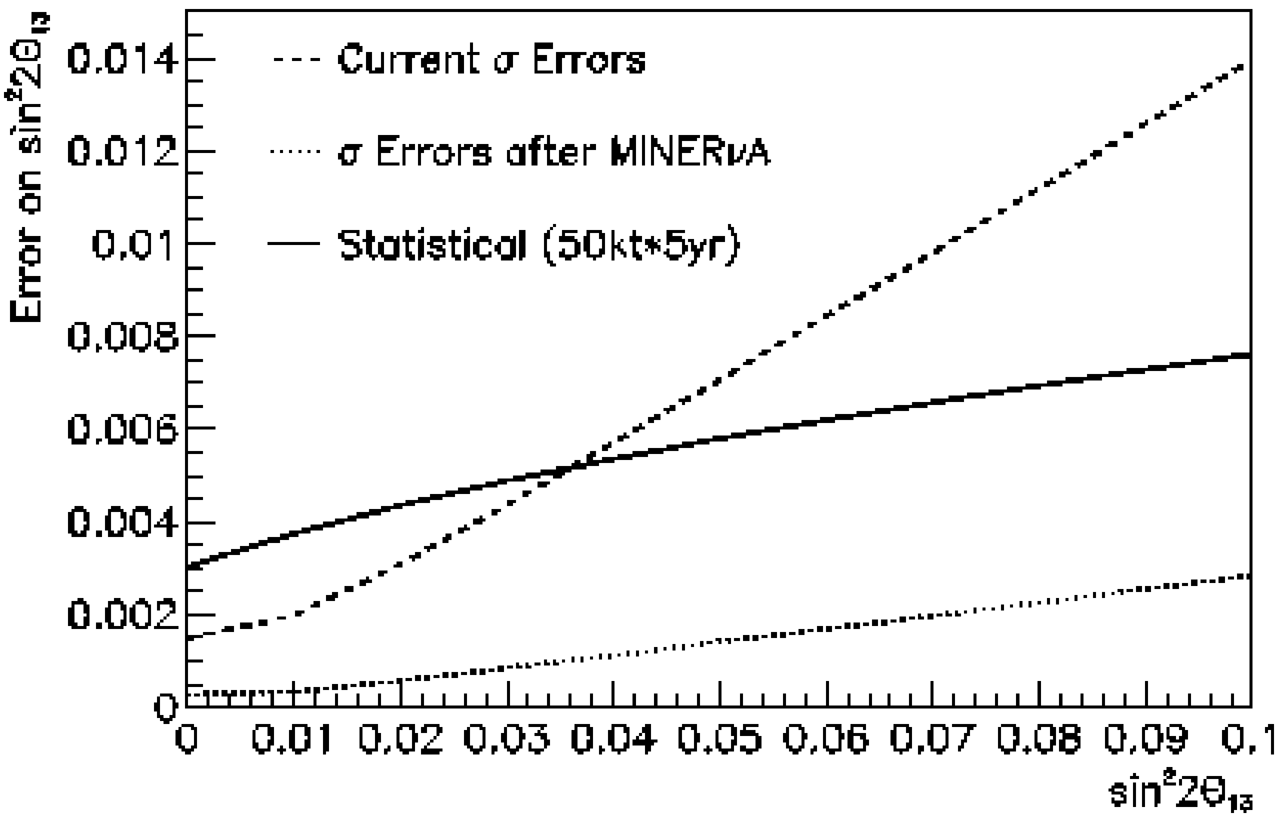


Minerva cross section errors



- Statistical Error is about 15% on background events alone

Cross Section Needs vs "$\sin^2 2\Theta_{13}$"

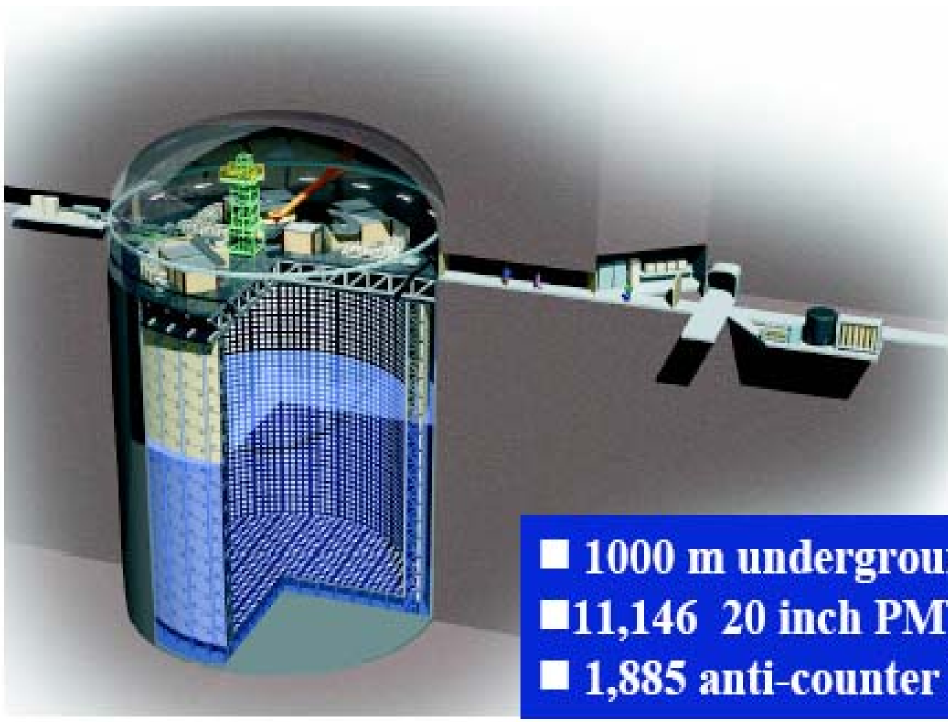


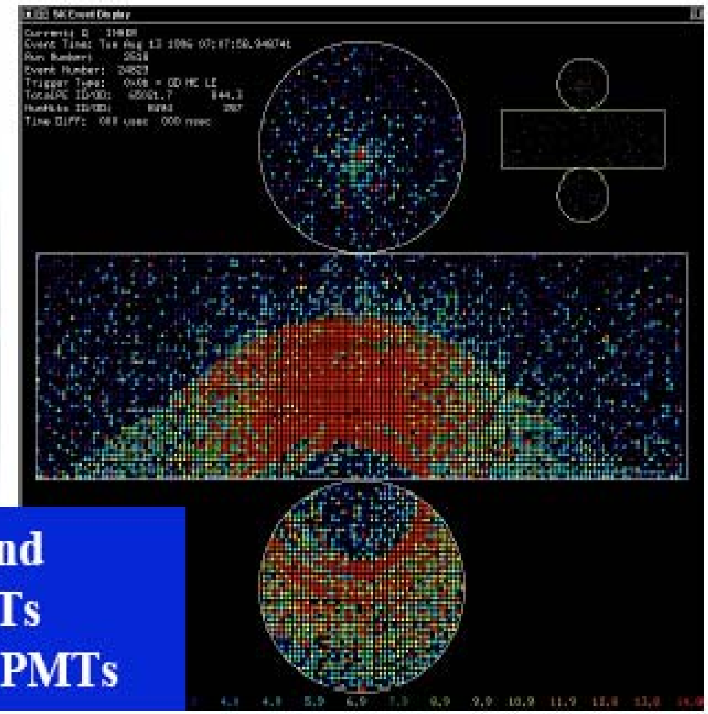
Two extremes:

With proton driver
And big signal,
Post-Minerva errors
Will be the same as
The statistical error

With proton driver and
No signal, post-minerva
Errors will be about half
The statistical error

SuperKamiokande Performance





- 1000 m underground
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

Response for single e,μ very well measured (test beam and cosmic rays)

But there are thresholds for detection…

- e; p > 0.6 MeV/c
- m; p > 120 MeV/c
- π; p > 160 MeV/c
- K; p > 563 MeV/c
- p; p > 1,070 MeV/c

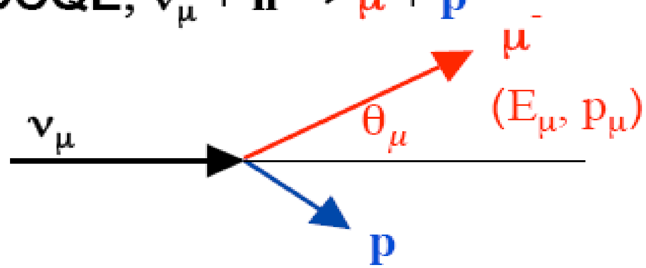
+ ~50MeV to identify a Cherenkov ring

Energy Reconstruction in Water Cerenkov

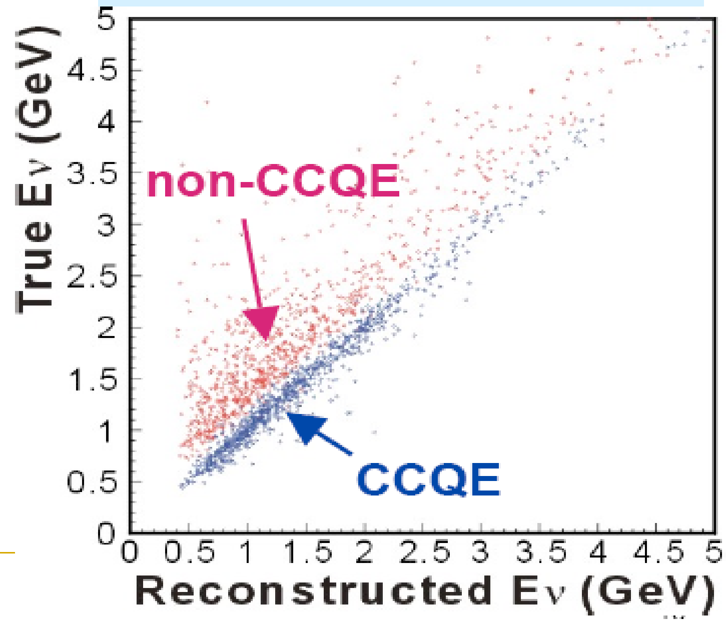
5. Neutrino Energy Reconstruction

Assuming CCQE, and μ information only

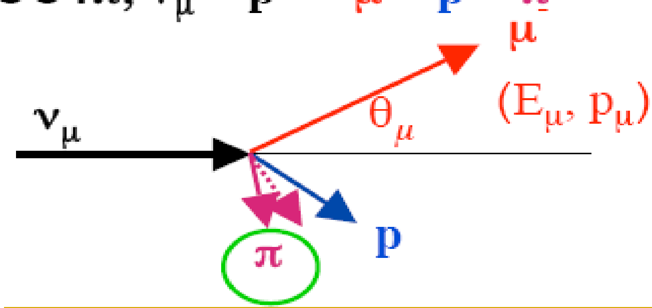
CCQE; $\nu_\mu + n \rightarrow \mu + p$



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$



CC1π; $\nu_\mu + p \rightarrow \mu + p + \pi$



From T.Nakaya, NuINT04

Which Cross-sections Matter?

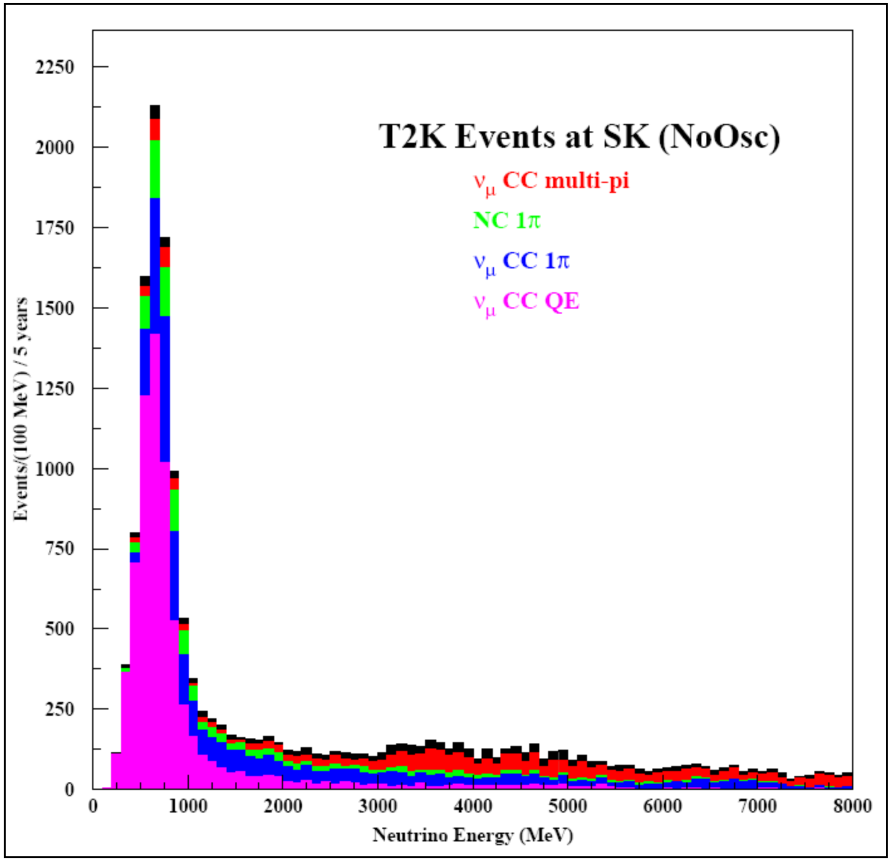
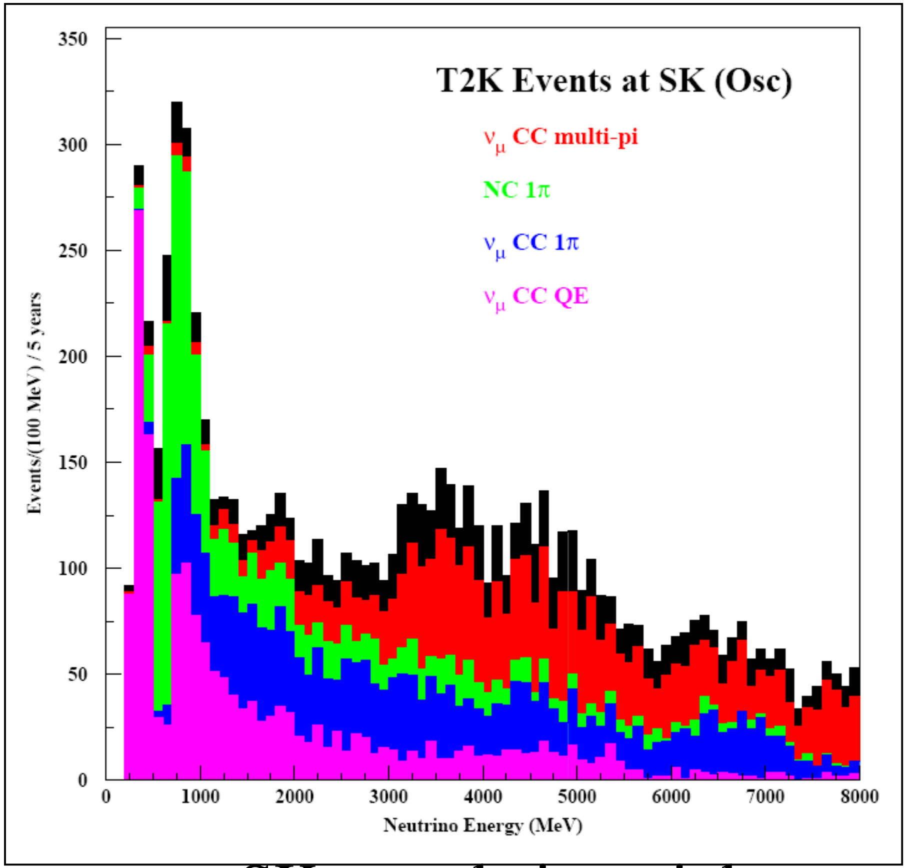


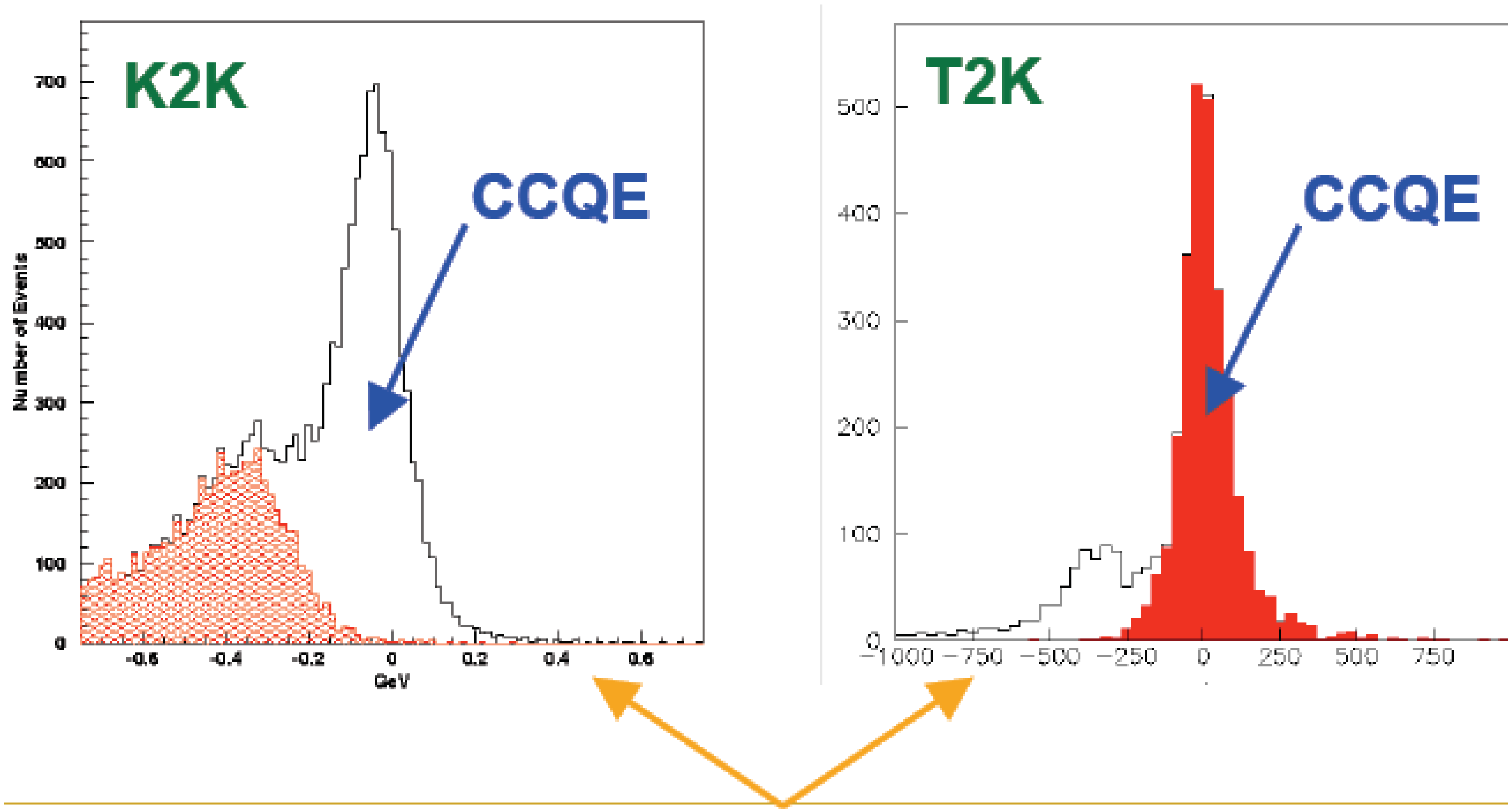
Figure courtesy D. Casper



SK sample is mainly non-QE!

How off in energy is non-QE sample?

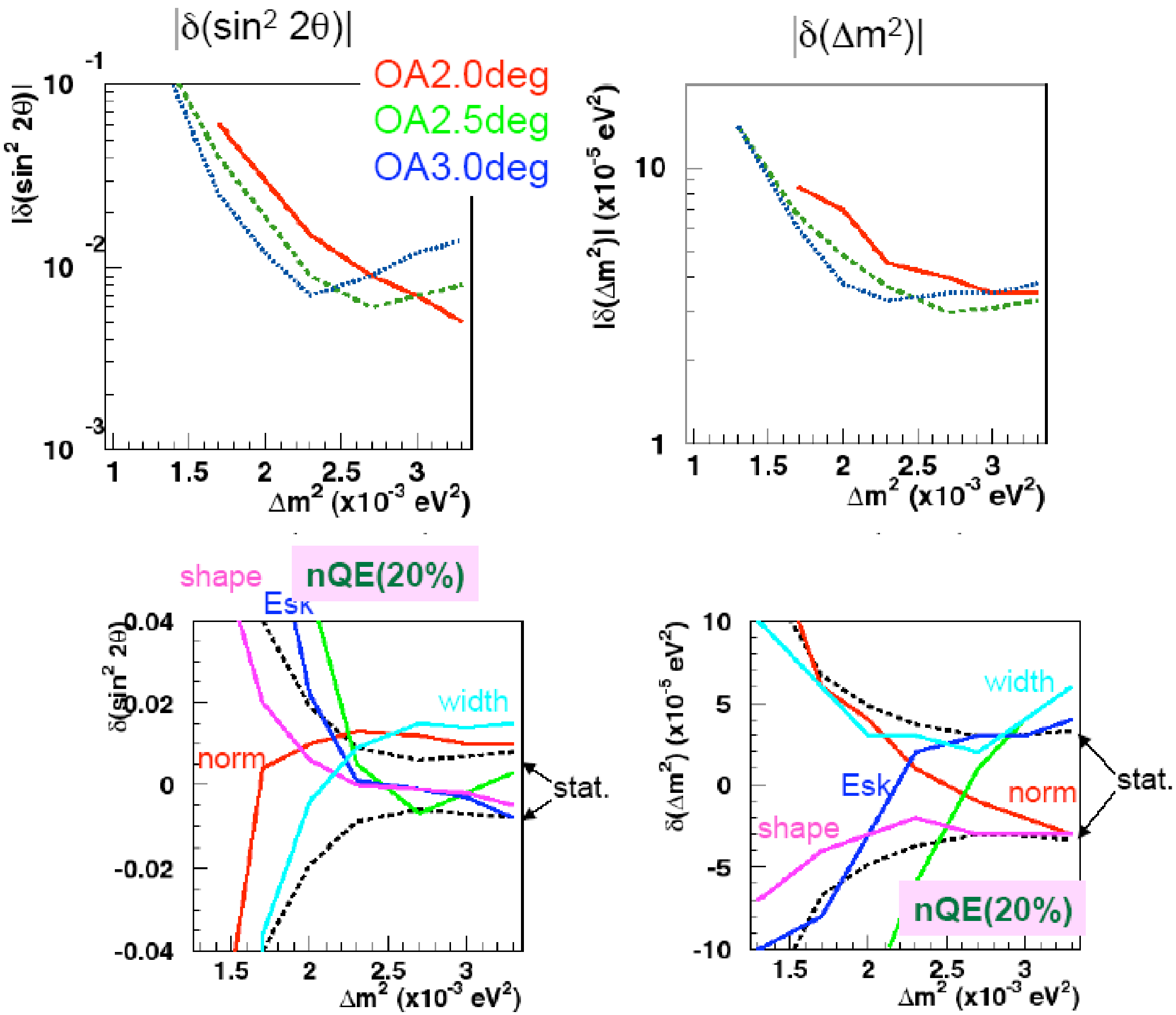
E_ν(reconstruct) – E_ν (True) (MeV)



Sorry, the color definitions of CCQE are different.

From T.Nakaya, NuINT04

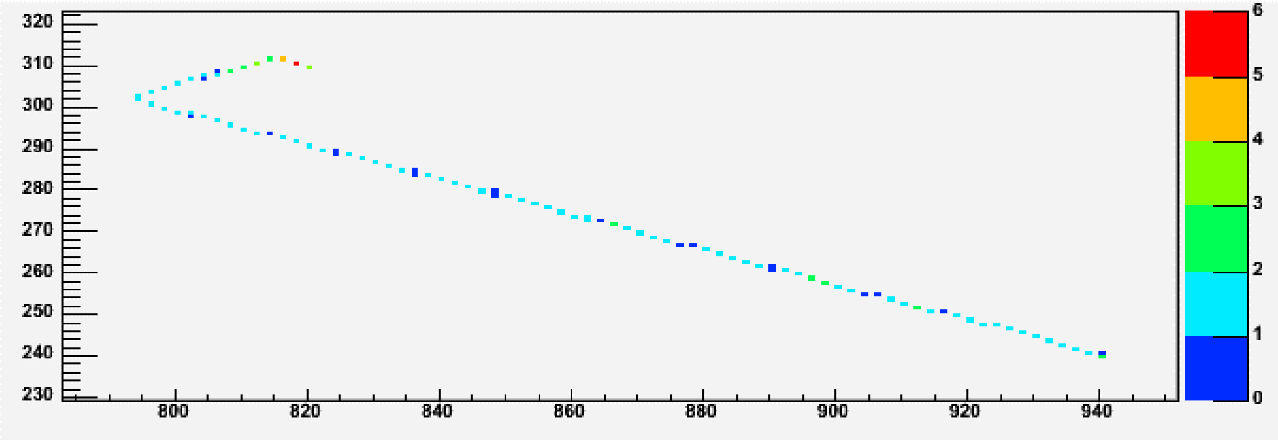
T2K Systematic Errors in $\sin^2 2\Theta_{23}, \Delta m^2_{23}$



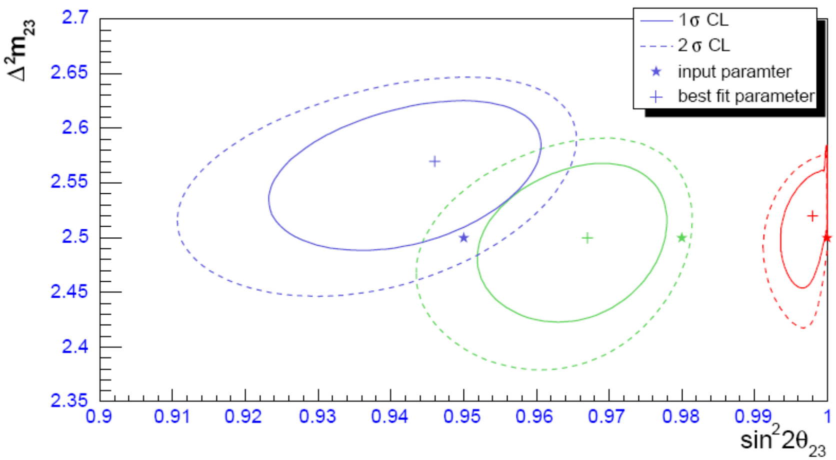
- Statistics in Phase I
- Systematics for 2.5° beam at the bottom: need better than 10% measurement of nQE!

Measuring ν_μ Disappearance in NOνA

Totally active scintillator detector:
Can identify QE's very well
(threshold much lower for p,π than water Cerenkov)



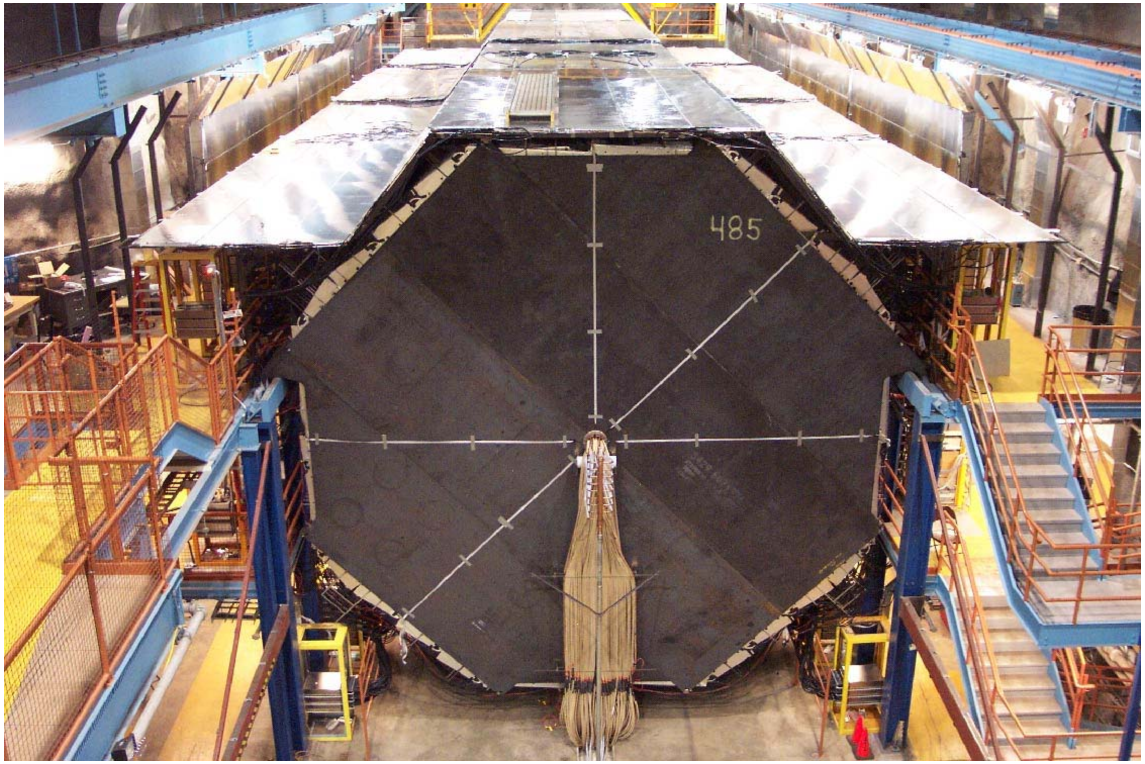
- Assuming Quasi-elastic events only, the statistical error is already at the 0.012 level for $\sin^2 2\Theta_{23}$, and .08-.10 for Δm^2_{23}
- Changing "energy loss mechanisms" in QE events gives systematic differences of .01 to .03 in error in sin2 $2\Theta_{23}$, but only .01-.04 in Δm2



Yang and Wojcicki, NOνA Note SIM-30

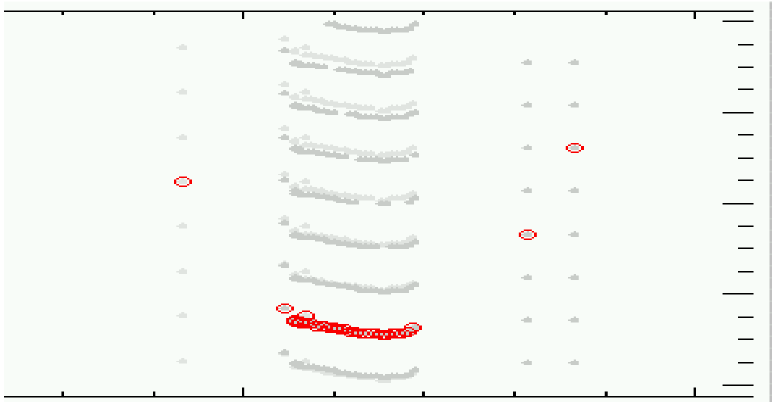
MINOS Detector

- 8m octagon steel & scintillator calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 5.4 kton total mass



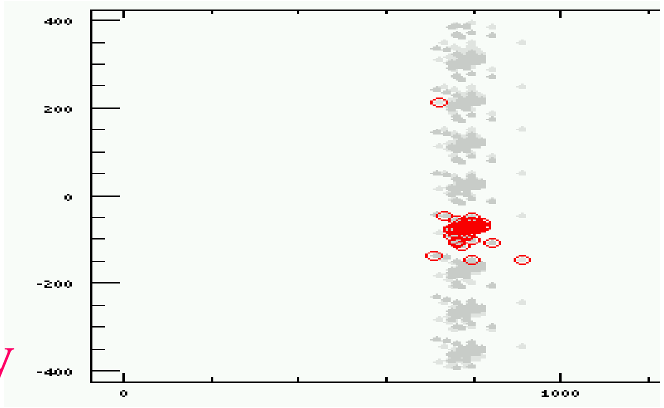
Primary Goal: ν_μ CC event reconstruction, kinetic energy measurement

Events at MINOS

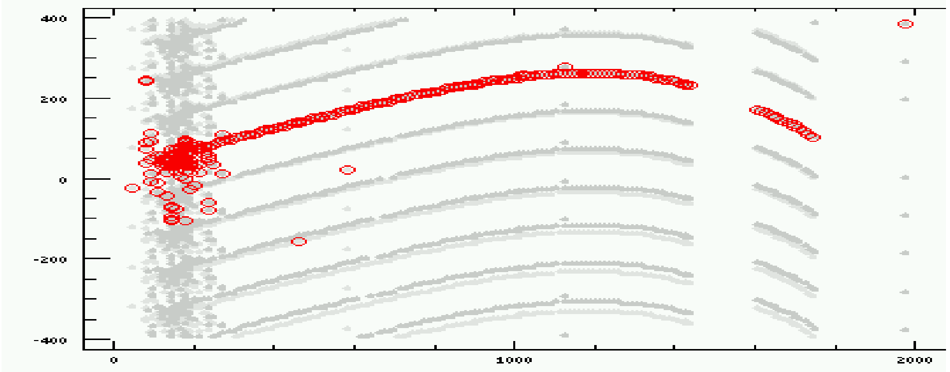


2.4GeV ν_μCC

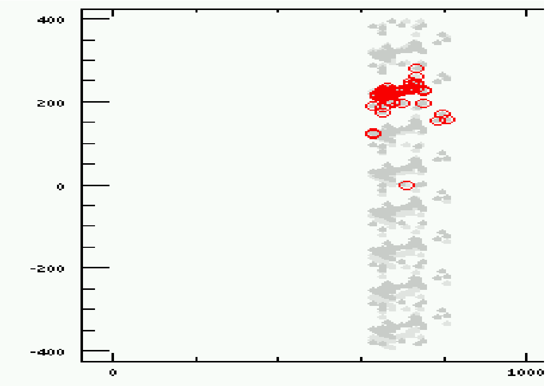
Courtesy
Mark
Messier



8.5GeV ν_eCC



25GeV ν_μCC



10GeV νNC

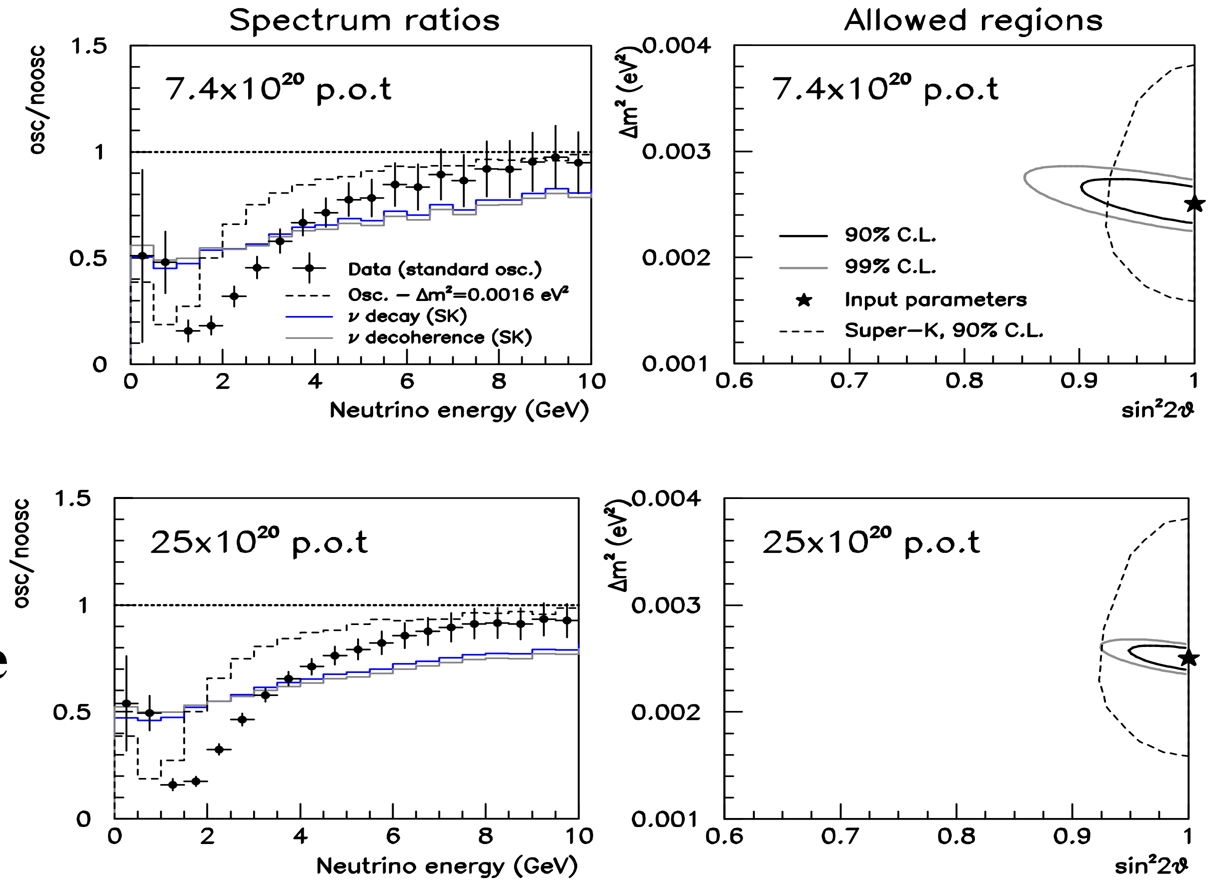
Measuring P("E$_\nu$") at MINOS

2.5 x 10^{20} Protons on target in 2005

Shown: plots for 7.4 and 25 x 10^{20}

NC backgrounds:

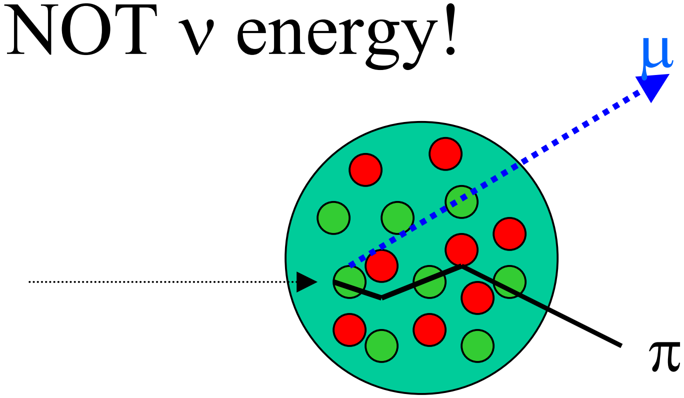
- **important for seeing the wiggle**
- **not important for precise Δm^2 measurement**

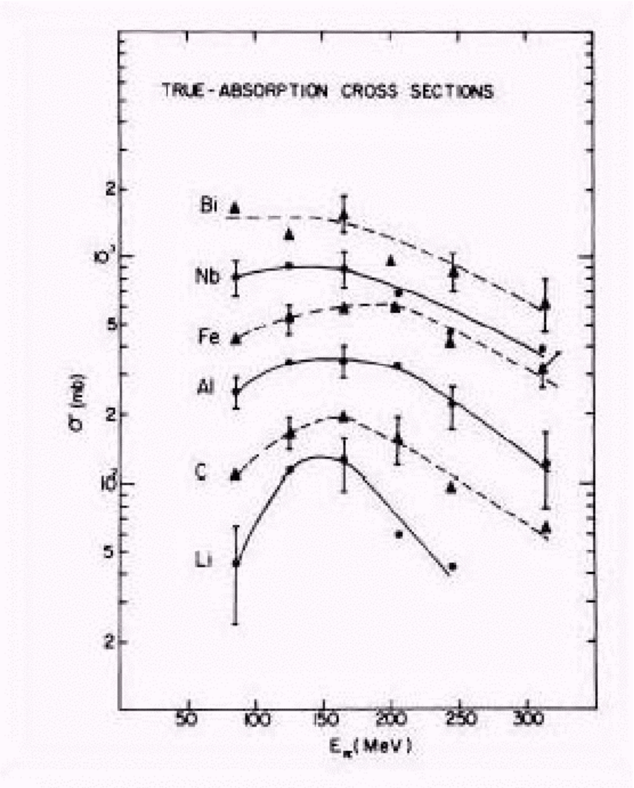


New Realm of Precision: details count!

Neutrino Energy Calibration

- Visible Energy in Calorimeter is NOT ν energy!
  - π absorption, rescattering
  - final state rest mass





D. Ashery et al, PRC **23**,1993

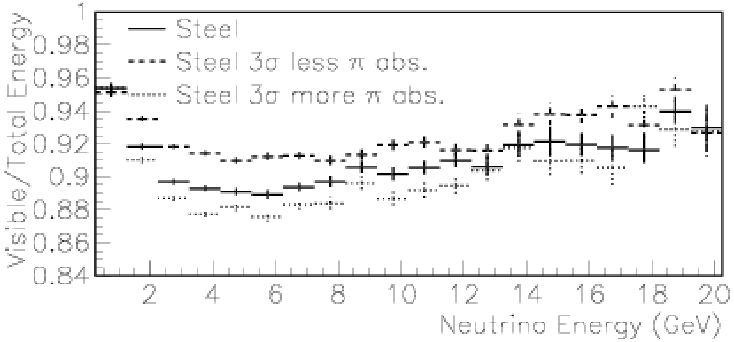
Nuclear Effects in neutrinos:
Pion Intranuclear Rescattering:
Comparison of Ne to D,
R. Merenyi et al, PRD **45**, 1992
(low statistics Bubble Chamber measurements, two separate beams)

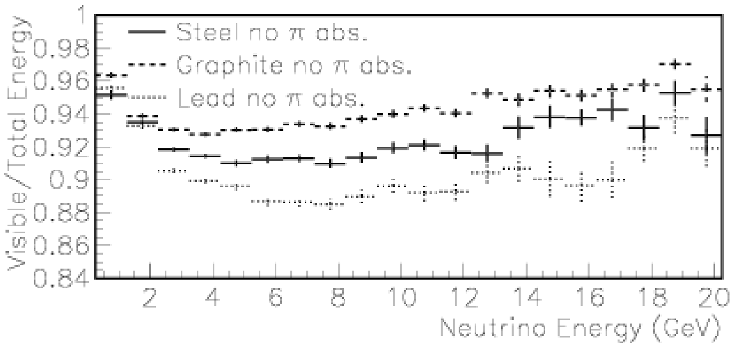
Nuclear Effects Studied in Charged Lepton Scattering, from Deuterium to Lead, at High energies, but nuclear corrections may be different between e/μ and ν scattering

How Nuclear Effects enter Δm^2 Analyses

Measurement of Δm^2 (e.g.MINOS)

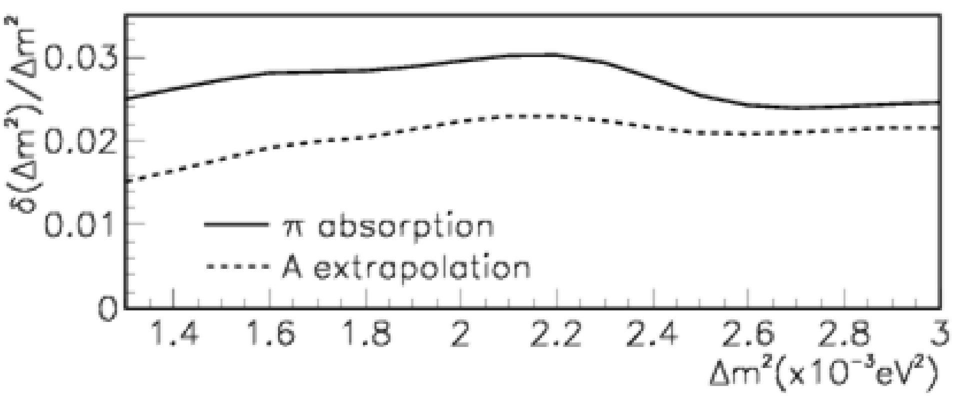
- Need to understand the relationship between the incoming neutrino energy and the visible energy in the detector





(rise due to muon energy cut of 0.75GeV)

Simple Analysis: shift the near to far prediction by these two Effects, after muon energy cut:

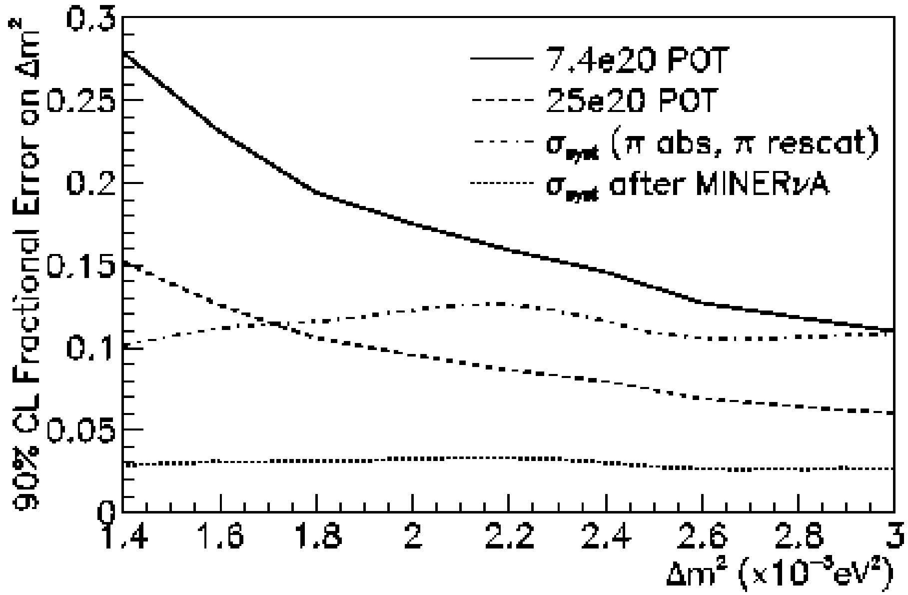


What is needed to improve the error on Δm^2_{23}

Ideally, want to measure cross sections on several different nuclei:

- Large span on target A
- Final state reconstruction
- Good vertexing so you know event-by-event what target nuclei is

MINERνA design: (before proton driver): pion absorption and rescattering measured on steel, carbon, lead…



MINOS analysis assumes these systematic uncertainties:

- 2% overall flux uncertainty
- MIPP bin-to-bin uncertainty
- 2% overall CC efficiency plus $(2-E_\nu)$*1.5% below 2GeV

And assumes systematic errors decrease with statistics

At Proton Driver Era:

Will want to still use MINOS to see ν_μ disappearance in antineutrinos…

Are nuclear effects the same there?

Conclusions

- ν_e appearance needs:
  - Coherent pion cross sections
    - Robust predictions from CC process to NC process
  - High y ν_μ cross sections
  - If signal is seen, we really need QE and Resonance cross sections better than we have now
- High Statistics ν_μ disappearance needs:
  - Measurements of Nuclear effects in neutrinos
  - "neutrino energy calibration"
  - Ratio of Quasi-elastic to non-Quasi-elastic cross sections